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During the grant period, Mr David Tulchinsky has been responsible for developing and applying new experimental techniques for probing the electronic and magnetic behavior of nanometer-scale structures with a high degree of temporal and spatial resolution. To this end, he has successfully designed a new family of digital magnetic semiconductor heterostructures and demonstrated the existence of digitally-fabricated quantum states using II-VI ZnSe/MnSe materials. these studies involved the construction of a femtosecond-resolved upconversion luminescence specroscopy system to monitor carrier dynamics at low temperatures (1- 300 K) and in relatively large magnetic fields (8T). In addition, he has been able to pattern these truly two-dimensional magnetic nanostructures into quasi-1D and zero-D systems using the focussed ion beam facility in the NSF Science and Technology Center at UCSB (QUEST). Cathodoluminescence measurements show structures as small as 50 nm may be fabricated for study in this fashion. Mr Tulchinsky received his Ph.D. in experimental physics based on the projects described below. He was immediately recruited as a postdoctoral researcher by scientists in the Electron Physics Group at NIST in Gaithersburg, MD. Dur to the success of his graduate work under the AASERT program, he subsequently was awarded a NRC Postdoctoral Fellowship to begin scanning electron beam polarization studies of low dimensional metallic heterostructures for science and technological applications.

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AASERT Final Technical Report

"Spatially-Resolved Spectroscopy and Imaging of Magnetic Nanostructures"

Grant # F49620-93-1-0446

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Department of Physics, University of California
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Mr. Tulchinsky received his Ph.D. in experimental physics based on the projects described below. He was immediately recruited as a postdoctoral researcher by scientists in the Electron Physics Group at NIST in Gaithersburg, MD. Due to the success of his graduate work under the AASERT program, he subsequently was awarded a NRC Postdoctoral Fellowship to begin scanning electron beam polarization studies of low dimensional metallic heterostructures for science and technological applications. A summary of his technical accomplishments follow.

- *Femtosecond Scattering Dynamics in Magnetic Semiconductor Spin Superlattices*

Spin-dependent dynamics of polarized carriers in a series of $Zn_{1-x}Mn_xSe/ZnSe$ superlattice structures have been directly observed by time-resolved (120 fs) upconversion photoluminescence spectroscopy at low temperatures. A magnetic field induces a complete spatial separation of exciton spin states with spin up carriers in the barriers and spin down carriers in the wells. In contrast to many theoretical expectations, polarization measurements in small magnetic fields reveal spin-flip scattering of excitons confined to a *magnetic* quantum well for the first time. In addition, a marked change in the dynamics is observed as the heterostructure goes through magnetic-field-induced changes in band alignment and subsequent "spin superlattice" formation. The exciton lifetimes and spin relaxation rates are seen to be strongly dependent on both the energy and *spatial location* of spin states in the superlattice, displaying dynamical behavior which is markedly different from that seen in ordinary quantum structures, including those composed of traditional MS heterostructures.

- *Femtosecond Spin Spectroscopy in Magnetically Tunable Heterostructures*

The dynamics of interacting carriers in quantum confined heterostructures continues to be an area of considerable experimental and theoretical interest, and has led to a deeper understanding of the energy relaxation process for excitons in semiconductor quantum wells. However, there are comparatively few investigations of <u>spin</u> dynamics in confined systems. A flexible system for studying the role of quantum confinement in spin relaxation is a double quantum well structure containing a diluted magnetic semiconductor separating barrier. This work utilized polarization-resolved photoluminescence measurements in which an initially polarized exciton population in subsequently monitored with femtosecond resolution. Systematic studies directly reveal spin-flip scattering between two Zeeman-split spin states, whose energy separation is continuously tunable by the applied field. The spin relaxation process is markedly dependent on the excitons' injection energy, <u>spin orientation</u>, and the Zeeman separation of the recombining carriers. Moreover, spin-selective relaxation of photoexcited carriers is directed by the breaking of spin degeneracy and magnetic control of the resulting scattering path. In particular, these measurements demonstrate the utility of all-optical spin spectroscopy in probing dynamical reorientation from magnetic layers of near atomic thicknesses.

- *Enhanced Spin Interactions in Digital Magnetic Heterostructures*

Mr. Tulchinsky was primarily responsible for developing new "digital magnetic heterostructures" (DMH) in which interactions between localized magnetic spins and their overlap with quantum-confined electronic states is tailored through a controlled digital distribution of two-dimensional (2D) magnetic layers. This class of quantum structures provides a widely tunable two-level electronic spin system with qualitatively different dynamical interactions than those seen in traditional diluted magnetic semiconductor (DMS) alloys. We have produced a comprehensive investigation of exciton spin-scattering and dynamic magnetization processes in DMH using both steady-state and time-resolved magneto-optical spectroscopies. Polarization-resolved luminescence measurements reveal spin-flip scattering between Zeeman-split levels that is strongly dependent on the energy splitting but *not* the local magnetic environment. These spin-engineered structures generate a giant "quantum confined" Faraday effect with optical rotations ~ 10^7 deg/cm-T *in a single 12 nm magnetic quantum well.* Following the picosecond electronic scattering process, Faraday rotation shows an induced magnetization with a remarkably slow temperature-dependent spin-lattice relaxation persisting to microsecond time scales. In contrast to alloyed magnetic semiconductors, rearranging the fixed number of moments within a comb of planes in otherwise identical quantum wells changes the number of nearest-neighbor interactions, enabling spin-dependent effects unlike those seen in three-dimensional alloys.

Presentations at International and National Conferences by Mr. David Tulchinsky:

1. D.A. Tulchinsky, J.F. Smyth, D.D. Awschalom, N. Samarth, H. Luo, J.K. Furdyna, "Femtosecond Spin-Polarization Spectroscopy in Magnetically Tuneable Heterostructures," International Workshop on Quantum Structures, University of California, Santa Barbara, CA, March 15-16, 1993.

2. D.A. Tulchinsky, J.F. Smyth, D.D. Awschalom, N. Samarth, H. Luo, and J.K. Furdyna, "Femtosecond Polarization Spectroscopy of Carriers in Magnetically-Coupled Double Quantum Wells," March Meeting of the American Physical Society, Seattle, Washington, March 21-25, 1993.

3. D.A. Tulchinsky, J.F. Smyth, D.D. Awschalom, N. Samarth, H. Luo and J.K. Furdyna, "Femtosecond Spin Dynamics in Magnetically Tunable Heterostructures," 20th International Conference on Low Temperature Physics, Eugene, Oregon, August 4-11, 1993.

4. D.A. Tulchinsky, D.D. Awschalom, N. Samarth, H. Luo and J.K. Furdyna, "Femtosecond Spin-Polarization Spectroscopy of Carriers in Magnetically Coupled Double Quantum Wells," March Meeting of the American Physical Society, Pittsburgh, PA, March 21-25, 1994.

5. D.A. Tulchinsky, D.D. Awschalom, R. Garcia, and N. Samarth, "Femtosecond Spin-Polarization Spectroscopy of Digital Magnetic Heterostructures", Meeting of the American Physical Society, San Jose, CA, March 21-28, 1995.

Papers Published in Refereed Journals by Mr. David Tulchinsky:

1. J. F. Smyth, D. A. Tulchinsky, D. D. Awschalom, N. Samarth, H. Luo, J. K. Furdyna, "Femtosecond Scattering Dynamics in Magnetic Semiconductor Spin Superlattices," *Phys. Rev. Lett.* **71**, 601 (1993).

2. D.A. Tulchinsky, J. F. Smyth, D. D. Awschalom, N. Samarth, H. Luo, J. K. Furdyna, "Femtosecond Spin Dynamics in Magnetically Tunable Heterostructures," Proceedings of the 20th International

Conference on Low Temperature Physics, Eugene, Oregon, August 4-11, 1993, *Physica B* **194-196**, 1305 (1994).

3. D.A. Tulchinsky, J. J. Baumberg, D. D. Awschalom, N. Samarth, H. Luo, J.K. Furdyna, "Femtosecond Spin Spectroscopy in Magnetically Tunable Heterostructures," *Phys. Rev. B*, Rapid Communications, **50**, 10851 (1994).

4. D.D. Awschalom, D. A. Tulchinsky, "Quantum Wells," *McGraw-Hill Yearbook of Science and Technology*, ed. Sybil Parker [Mc-Graw Hill: NY, (1996)], p. 281-283.

5. S.A. Crooker, D. A. Tulchinsky, J. Levy, D. D. Awschalom, R. Garcia, N. Samarth, "Enhanced Spin Interactions in Digital Magnetic Heterostructures," *Physical Review Lett.*, **75**, 505 (1995).

6. D.A. Tulchinsky, S. A. Crooker, J. Levy, V. Nikitin, N. Samarth, and D. D. Awschalom, "New Dynamical Spectroscopies in Digital Magnetic Heterostructures," *Proceedings of the Conference on Physical Phenomena in High Magnetic Fields*, ed. by Lev Gorkov [World Scientific, London, 1996].